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Title: # Technological evolution - an economic perspective

Field of study: Technology Strategies

Purpose: Dissertation for obtaining the Degree of Master in Business Administration (The Lisbon MBA International)

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Date: 28-02-2013

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Abstract

The evolution of a technology and the understanding of the moment in its life cycle is of the utmost importance to the entry strategy devised by any company.

Having the entry of EDP Brazil on the micro-generation market as background, the present work-project attempts to summarize the most important topics in management literature concerning the theory of technology life-cycles and the updated literature on developments of photovoltaic technology to infer the current positioning of this technology in the theoretical models.

The need for this type of work stems from the very common lack of bridging between the academic research of economic aspects relevant to the evolution of technologies and the agents of research on specific technological issues. When this occurs, namely due to the external nature of research to companies, thereby escaping the harsh economic controls of a profit seeking enterprise, the evolution many times lacks the appropriate framework to be studied on a more forward looking manner and to allow for management decisions to be based on.

1. Introduction

The present work project stems from a consultancy project made for EDP Brazil, as this company set forth the target to penetrate a very immature distributed generation market based on the photovoltaic technology.

Although the consultancy project was briefed with a specific technology in mind and was marketing oriented, the team discussed several times the importance of the choice of technology and how this choice offsets all other subsequent pricing and marketing options. As such discussions surfaced, the general need to understand the reasons behind such a choice in technology and confront it with its pros and cons while relating back to the moment of the product life-cycle, became apparent. This work sets out on that trail, trying to give an answer to the following question: "What is the moment in the photovoltaic technology life-cycle and, according to theory, what challenges and benefits can be expected for an entrance in the market?"

The production of energy has doubled from 1973 to 2010 (IEA, 2012). The ability to meet demand has so far been attributable to the increase in fossil fuel consumption. However, to allow for a continued increase in the exploitation of natural resources is to forget the need for sustainability in the long run, but to devise an alternative production system is by no means simple.

Faced with the need to find alternatives that do not compromise the economic expansion that has characterized the last decades, mankind has deposited high hopes in technological innovations to fill this gap, be it through advances in energy efficient substitutes or the renewable energy production.

Although with huge significance in the last 20 years, "innovation" is by no means a recent concept.

One may remember that Adam Smith pioneered the idea of the subdivision of labor to achieve greater efficiencies. In his book "Wealth of Nations" (Smith, 1776), this renowned author also brings about the notion of improvements in machinery being conducive to a better use of labor and therefore economies in the cost of the product and growth in the overall supply.

Much later on, Rosenberg's (Rosenberg, 1976) paper on Marx's views states quite clearly that "... the social and economic structure of capitalism is one which creates enormous incentives for the generation of technological change" and "the very essence of bourgeois rule is technological dynamism" as "Capitalism generates unique incentives for the introduction of new, cost-reducing technologies".

Indeed Marx's and Engels' "creative destruction" has its basis in the notion that for there to be a development in the economy under a capitalist regime, there must first be a destruction of previous productive forces and production, which undoubtedly has parallels to the product and process life-cycles, as Schumpeter gathered (Schumpeter, Business Cycles, 1939). The role played by Science in the evolution of the way things are done is determined to be fundamental. Schumpeter further explains the difference between invention and innovation, stating that innovation relates to changes in the methods whereas invention is an immaterial concept with no direct economic impact. The creative destruction is then applied to circle the opportunity of continuous progress, allowing for the improvement of life standards for all society.

These views on innovation and the increased pace at which R&D has permeated the discoveries on the technology dependent society has led several renowned scholars to debate the same life-cycle concepts and models in an attempt to justify the similarities between different products. Indeed the link has been established and several empiric evidences may be shown to attest the recurrence of the cycle.

The specific technology in this work - photovoltaic (PV) has benefitted from a history of developments dating back to 1839. However, the challenges posed meant a less than continuous effort on behalf of scientists, and the evolution lagged behind when compared to alternative sources of electricity, such as chemical (gas, coal, fuel) or even the development of other renewables (wind, hydro).

After a brief introduction to the several sub-technologies under the photovoltaic (PV) umbrella, it is therefore interesting to approach the evolution of the PV from an historical perspective to better understand the bursts in research and demand, and the roles several actors had in it, from the single buyer to government policies.

These historical concepts will help to drive the point that technological change has been a studied subject for a while now, namely due to its great impact in the evolution of the economy and the relation between labor and capital. Understanding the impacts and structure of innovation will therefore lead to a deeper knowledge of what the economy may expect from its different sectors, and help the sectors organize according to the expectations around the technologies.

The Energy sector is no stranger to technological evolution. From the initial coal fired power plants to the most modern nuclear fission ones, the steps taken have rendered many predictably stable designs obsolete. Now with the renewables' technology this impact stands to be great, as the drive for cleaner alternatives pushes for government backed grants to developers and distorts market opportunities, rendering investments in R&D unnecessary.

Finally, the two distinct parts of the work will combine to demonstrate the applicability of the theoretical models and allow the reader to better understand the challenges faced by this technology on the approach to the next level of the product life-cycle curve and understand if it is feasible to pinpoint the current moment in the product life-cycle of photovoltaic technology.

2. The Photovoltaic technology basics

In a paper where PV technology is discussed it is important to go through the basics of the technology. As such, the present chapter explains what is the photovoltaic effect and the differences between four subtypes of this technology.

The photovoltaic effect is a phenomenon that occurs with the incidence of radiation upon the PV cell. The radiation contains energy (photons) that goes through two semiconductor layers and is transmitted to electrons on the positively charged layer, freeing them from their orbit. When freed, the electrons naturally drift to the negative terminal due to an existing electrical field within the cell. Once given a pathway of return, the freed electrons flow through the exterior of the cell, creating a current. The following image systematizes the explanation:

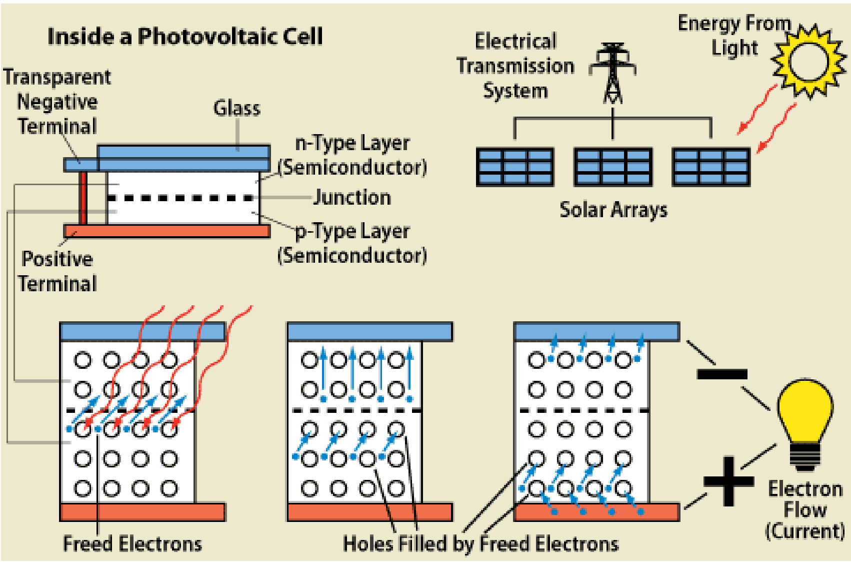


Figure 1 - Photovoltaic effect. Source: US DOE

Photovoltaic technology may be disaggregated into four different generations:

1. Crystalline Silicon (c-Si) - Be it single-crystalline (sc-Si) or multi-crystalline (mc-Si), these are the most common solar cell types;
2. Thin Film technologies;
3. From concentrating technologies that make use of high efficiency cells;
4. Dye-sensitized cells (still unproven technologies not widely available in the market).

To better understand the technology evolution, one must first understand the particularities of the different sub-technologies.

Crystalline silicon cells:

As one of the most abundant materials on the planet, the fact that silicon's inherent properties make it a viable semi-conductor for PV applications makes it the current most relevant element in the industry.

Crystalline silicon cells may be of growth of a single crystal (in which case they are called monocrystalline) or several (multicrystalline). Although more difficult to produce, and hence more expensive, monocrystalline structures offer better efficiency.

The production of silicon cells started in 1963, and the evolution of efficiency has been a constant, now ranging from 14% to 19%, and represented about 87% of the market in 2010.

Thin film

As the name indicates, these cells are manufactured by the deposition of extremely thin layers of semiconductor (around 3 µm thick), allowing for great cost reduction at the expense of only a fraction of efficiency.

The semiconductor used in the thin film technology may be of amorphous silicon, cadmium telluride, Copper-Indium-Selenide (CIS) or further adding Galium for a CIGS cell. The respective efficiencies range up to 8% for the amorphous silicon and 16% for the remainders.

Although cheaper in production, several thin film technologies have registered a rapid decline in efficiency of the cell with continued exposure to the sun, and the use of rarer materials such as tellurium (a by-product of the chemical copper treating process) hinder a potentially accelerated growth of market

Concentrating technologies

There have been considerable advances in cell efficiency, having already crossed the 40% threshold. However, the type of materials used for such devices are rare and costly (e.g. gallium, arsenide or Indium). These cells are constructed as multijuntion, usually in stack as to allow for different wave-lengthed photons to be captured.

To increase the efficiency and reduce the need for these rare materials, concentration by means of lenses is used. This usually also means the need for sun-tracking - a single or double axis structure to keep the sun from tilting to an angle to the cell that does not maximize the concentration of solar rays.

As the complexity increases, so does cost. This type of technology is seldom used, representing but a fraction of the overall PV market.

Dye sensitized cells, organic cells and other forward looking types

Despite the attractiveness that stems from the low cost materials used in the production of dye sensitized of cells, the 4% commercial grade cells' efficiency and the low life span due to UV exposure make for the small market penetration. However, the use of nanotechnology in the design of synthesized dyes offers a promising outlook on this technology.

Made from organic materials, organic solar cells are at the very low end of PV efficiency (6%), but are still mentioned in literature due to their low cost and lightweight and flexible components that may be used in diverse applications ranging from buildings to mobile phones.

Based on nanotechnology, several designs have emerged as promising for the evolution of the solar cell concept. From nano antennas that are able to tune into the solar radiation's frequency and convert it to electricity (much like TV antennas used to do with the broadcasting signal) to even more futuristic approaches such as quantum dots, acting in a similar manner to the multi-junction cells, but with the ability to "tune" the band gap and not be restricted by the element's properties.

Having gone through the basics of the technologies, one immediately notices the fact that there is no "one standard" to this technology. However, it should be noted that crystalline silicon currently holds around 90% of the market as may be seen in the following table.

		1st Generation PV		2nd Generation PV			3rd Generation PV		
Technology	Units	Single crystalline silicon (sc-Si)	Polycrystalline silicon (pc-Si)	Amorphous silicon (a-Si)	Copper Indium Gallium Diselenide (CIS/ CIGS)	Cadmium Telluride solar cells (CdTe)	III-V compound Multijunction, Concentrated PV (CPV)	Dye-sensitized (DSSC)	Organic or Polymer (OPV)
Best research solar cell efficiency at AM1.5*	%	24.7		10.4 Single junction 13.2 Tandem	20.3	16.5	43.5	11.1	11.1
Confirmed solar cell efficiency at AM1.5	%	20-24	14-18	6-8	10-12	8-10	36-41	8.8	8.3
Commercial PV Module efficiency at AM1.5	%	15-19	13-15	5-8	7-11	8-11	25-30	1-5	1
Confirmed maximum PV Module efficiency	%	23	16	7.1/ 10.0	12.1	11.2	25	-	-
Current PV module cost	USD/W	< 1.4	< 1.4	~ 0.8	~ 0.9	~ 0.9	-	-	-
Market share in 2009	%	83	3	1	13		-	-	-
Market share in 2010	%	87	2	2	9		-	-	-
Maximum PV module output power	W		320	300	120	120	120	-	-
PV module size	m^2	2.0	1.4-2.5	1.4	0.6-1.0	0.72	-	-	-
Area needed per kW	m^2	7	8	15	10	11	-	-	-
State of commercialisation		Mature with large-scale production	Mature with large-scale production	Early deployment phase, medium-scale production	Early deployment phase, medium-scale production	Early deployment phase, small-scale production	Just commercialised, small-scale production	R&D phase	R&D phase

Figure 2 - PV sub-technologies' market share. Source: IRENA

Note: all values registered at Normal Operating Cell Temperature (NOCT)

3. The evolution of a technology - A theoretical point of view

As mentioned in the introduction, the ability and consequences of innovative firms have been approached by figures such as Adam Smith or Karl Marx, defining innovation as the way to continuously achieve higher levels of output efficiency.

The present chapter will offer a comprehensive view on the evolution of technology, focusing on the distinction of the invention and innovation concepts, appropriability fears, the product, process and technology life-cycle models and the need for existing complementary assets.

Invention Vs. Innovation

Although many times misused, these concepts are sometimes mentioned in the literature as complimentary, but not the same. Schumpeter's work states that "innovation" is the "setting up of a new production function (...) combining factors in a new way" (Schumpeter, Business Cycles, 1939). Invention, according to the same author, however, need not have a direct applicability to the production and therefore may not alter the status quo. To this point it may be read that "The inventions of the antique world and the middle ages for centuries failed to affect the current of life".

This distinction between the two concepts is further explained by Freeman and Soete in their "Economics of Industrial Innovation" (Freeman, C. & Soete, L., 1997) by stating that "invention is an idea ... for a new or improved device, product, process or system. Such inventions ... do not necessarily lead to technical innovations. (...) An innovation ... is accomplished only with the first commercial transaction involving the new product, process system or device".

When confronted the concepts to the neoclassical idea of business, one may find some shortcomings.

Prior to Keynes, the neoclassical economics stated that all individuals are rational and act to maximize profit on the basis of full information. It stands to reason then, that if firms only act upon opportunities of return, the possibility of investing in general science would be unreasonable, as the returns would be, at best, dubious. As such, inventions would seldom happen in the corporate world, whereas innovations, as direct applications and adherence to the bottom-line, would be favored.

Several authors have come to discredit this theory, namely Mowery and Rosenberg (Mowery, D. & Rosenberg, N., 1991) that simply show that in such a world, when all science would be advanced by public spending and not by private firms, all researchers would be employed by the government, leaving the firms empty of resources to then search for a direct and application with positive returns. One special case that illustrates this is the fact that technological advances fueled by the war effort found their way into civilian applications, but companies struggled to interpret the science, as the lack of in-house knowledge was apparent.

After the crumble of the expectation that all individuals are rational with the 1930s depression, several new economic theories started to emerge, and the central issue was the competitiveness of the firms in a world of limited resources. This concern is still central to all innovative firms, and steers the issue to the way in which an innovation may benefit the innovator, and not the competition.

Appropriability

In an article on the Harvard Business Review, Ikujiro Nonaka (Nonaka, 2007) states that when the whole economy is based on uncertainty, the only true source of competitive advantage is knowledge. Recognizing the need to have the resources to not only create knowledge, but also decode it, companies strive to capture the best researchers and practitioners, which many times implies allowing for research to advance without a specific purpose, again shattering the neoclassical model.

Once the correct skills are acquired, the development of technologies stands on the ability to combine previous knowledge. Codification - making the knowledge explicit - is necessary to allow transference within the firm at lower cost, but one must also account for the ease of transference of knowledge to the outside of the firm. Be it through lectures, conferences, internet leaks or the fact that people change jobs, the discussion regarding the need for some protection is a constant. Indeed, if no measures are taken, one stands to lose ground to competitors that may "learn from not doing" (Saviotti, 1998) which is "faster, simpler and less costly". However, the interpretation of knowledge may not be straightforward, and as technologies grow more complex, so does the interpretation of discoveries.

In 1962 Arrow (Dosi, G., Malerba, F., Ramello, G, Silva, F., 2006) had already understood the differences between information and other commodities, namely the fact that it may be used by several users at the same time, or the difficulty in naming and accepting a price by a piece of knowledge. This author is credited with the discovery of the "Arrow Paradox", whereby the potential buyer has limited knowledge to understand the value of the information to buy, but if enough information is shared for a correct valuation, no sale is then possible.

If this transference of knowledge is costly to the developer, and difficult to put a price on by the possible buyer, appropriability is then a crucial aspect, but may derive not only through the use of legal mechanisms (patents, trademarks, etc) or the silence of employees, but also by factors intrinsic to the technology, such as the fact that it combines knowledge from multiple domains or the lack of complementary assets. Another issue raised by Saviotti (Saviotti, 1998) stems from the change in appropriability with the evolution on the life cycle of the technology. As it matures, the ease of imitation increases. One strategy is to advance the frontier as fast as possible, compensating for the increase in codification that is usual for maturing technologies. This is a widely used strategy for hi-tech companies, but not a reasonable one for commodities.

On the other hand, Dosi (Dosi, G., Malerba, F., Ramello, G, Silva, F., 2006) brings about a different link between appropriability and innovation, stating how a sector in which appropriability is absolute distorts the market into a monopoly, hindering any advantage in innovation except for ones concerned with reduction of cost and therefore increment in supplier profit.

Cumulative knowledge and the incremental difficulty of arriving late to an industry with high embedded tacit knowledge increases the entry barriers to a point where only if the margins are still high due to lack of competition does it make sense for a newcomer. Competition, on the other hand, may be expected to be a function of the stage on a life-cycle of a specific industry. To better understand the life-cycle concept, one must start by discerning between three often mixed up concepts.

Product Life-cycle (PLC), Industry Life-cycle (ILC) and Technology Life-cycle (TLC)

Although distinct in nature, these three life-cycles have often been confused and their respective terminologies used in less than proper ways (Taylor, M., Taylor, A., 2012). As such, and before exploring the technology life-cycle, it is worth to note the differences and clarify the reasoning for the use of the TLC as a predictive method for management decision making.

Product Life-Cycle

The most widely known of the three life-cycles to be depicted (Taylor, M., Taylor, A., 2012), the PLC was the systematization of the regular evolution encountered when studying the evolution of products. In a 1997 paper, Steven Klepper (Klepper, 1997) gathers the views on the PLC of several scholars and synthesizes the concept in three stages: the initial stage in which volume is low, the product is a first concept with much to tune, production is unspecialized to allow for tweaking and uncertainty is high; then comes the growth stage, with a stabilization of product design, massification of demand and corresponding supply, the process innovation gains ground to the initial product oriented innovation; lastly, the mature stage steps in with the stabilization of the design, the lower demand for products and decline of the design. Other authors have further broken down the phases in the PLC, namely by separating the "mature stage" into "mature" and "decline" stages. A simple illustration of how sales of the product relate to the stage in the PLC allows for clarification of the concept:

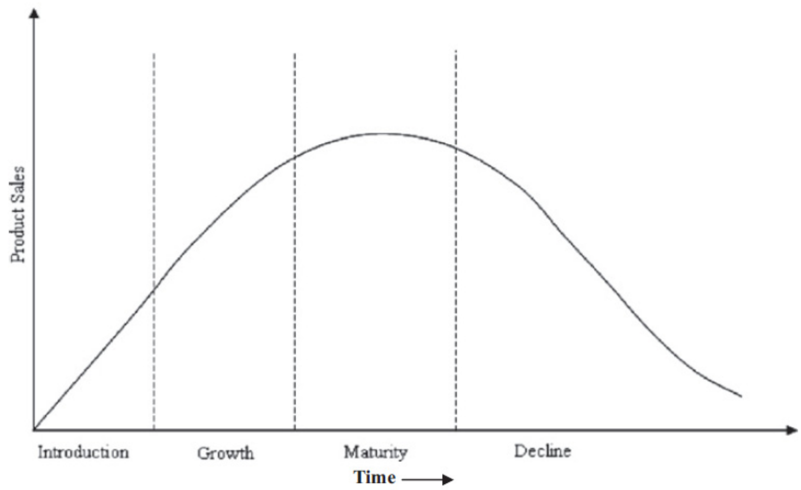


Figure 3 - Sales along the product life-cycle. Source: Taylor & Taylor, 2012

The Industry Life-cycle

Klepper (Klepper, 1997) based an approach on the Product Life-Cycle to conjecture on the existence of a similar model that would apply to a whole industry and capture the evolutionary pattern. What was found was that the industry suffered through the same sort of pattern of introduction, growth and maturity (and decline), with a large number of players in the beginning and a sharp decline as the industry grows and matures. The reasons for this occurrence have to do with the need for specialization of production and the fact that few incumbents bet on what later becomes the stabilized model of the product.

Both the PLC and the ILC have offered some comfort to management decisions (Taylor, M., Taylor, A., 2012) (Klepper, 1997). However, the fact that the models' curve applies says little about the actual curvature (the length of each of the different stages). As such, management is left wondering if the estimated current point in the industry life-cycle is sufficiently exact to make inferences as to enter or not enter the market. As stated by Taylor and Taylor, "both the PLC and the ILC are, at best, partial proxies for technology progression". Because technology and the evolution is what really matters, the technology life-cycle was discussed by these authors.

Technology Life-Cycle

The approach to the evolution of the technology Life-Cycle was gathered mostly by Anderson and Tushman, on a work called "Technological Discontinuities and Dominant Designs" (Anderson, Tushman, Dec. 1990), in which Schumpeter's (Schumpeter, The theory of economic development 4th Edition, 1951) technological path is revisited with issues such as the resistance to change and the need for a minimum adherence before the new technology takes off.

The Anderson and Tushman model systematized looks like the following figure:

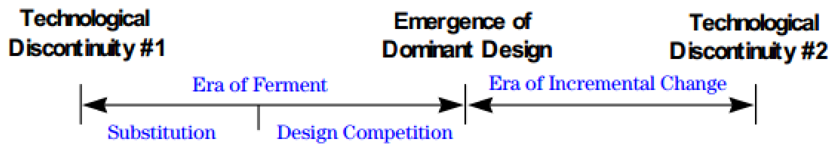


Figure 4 - The technological life-cycle. Source: Adapted from Anderson and Tushman, 1990

The cycle is composed of three major events and two periods in between events.

Technological Discontinuity

A discontinuity is reached when the technological shift is one that significantly alters the price/performance balance of an industry. As a consequence, the sustainability of a company may rely on the adoption of the new paradigm.

Taylor and Taylor (2012) refer to Pyka (2000) to clarify that discontinuities may be of two types - Product or Process. The former takes place with the emergence of a new product that renders the existing ones obsolete. As it happened with the DVD related to the VHS player, the new product drives sales of the incumbent to a non-sustainable level. The latter form of discontinuity (Process) may alter dramatically the balance between labor and capital on the production level or may lead to large changes in the cost. Automation of production is one such example.

With the emergence of the discontinuity, an era of ferment takes place.

Era of ferment

Even with the recognition of a discontinuity, the adoption seldom happens immediately. Several initial trials are usually made, as the industry takes its time to adjust. In the famous work by Nathan Rosenberg "On Technological Expectations" (Rosenberg, 1976) the author uses De Tocqueville's experience with the change in ships in America to explain the need for a stabilization of the innovation if there is to be a generalized adoption. The era of ferment offers just this opportunity, with product substitution and competition among emerging designs finding their way into the market.

Another well known example of an era of ferment, and bringing the discussion to the Energy sector, is the period later known as "The War of Currents". This period in the late 1880s became known for the emergence of electricity and the opposition of the defendants of a direct current system (Thomas Edison) and the defendants of an alternate current system (Nikola Tesla and George Westinghouse). It took years before the settling of a standard, and the competition between the two was fierce, each using technical arguments to convince adopters. Eventually, the alternate current system proved to be better, and Edison eventually conceded in his defeat.

When one design emerges as the optimal, the moment is called "Emergence of the Dominant Design"

Emergence of the Dominant Design and Incremental Change

Once a specific design has emerged as the chosen one, the level of standardization increases and the focus is brought upon production improvements (Teece, 1992), evolving in terms of cost reduction. Another important characteristic of this era is the testing implied by the availability of the new technology on the market. Where only the early innovators stood moments earlier, with the emergence of the dominant design the large majority of consumers now adhere to the technology and start the massive testing necessary to pinpoint the flaws and needed corrections.

Considering the Fluid time as one of early technological development, the Transitional as the period post market acceptance and the Specific as a time when most all developments have been made, resulting in a commodity market, the following figure represents the flow of innovations by type.

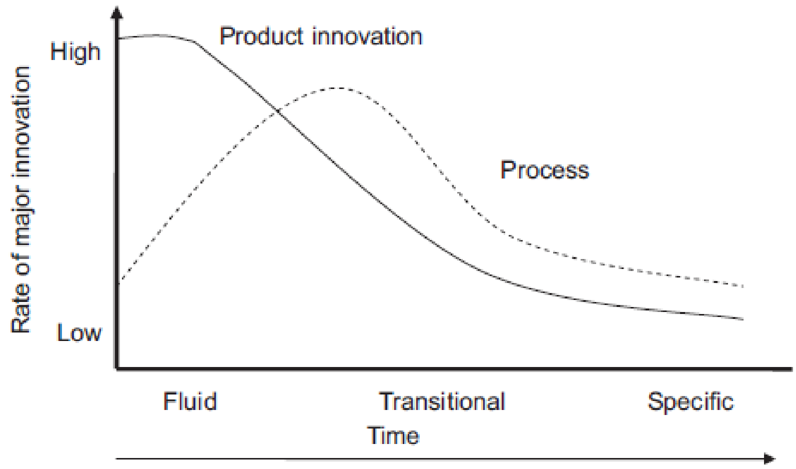


Figure 5 - Product and process innovation. Source: Utterback *in* Taylor & Taylor, 2012

The S shape

As a corollary of the technological evolution process, the advances are seen to obey an S-shaped graph as follows:

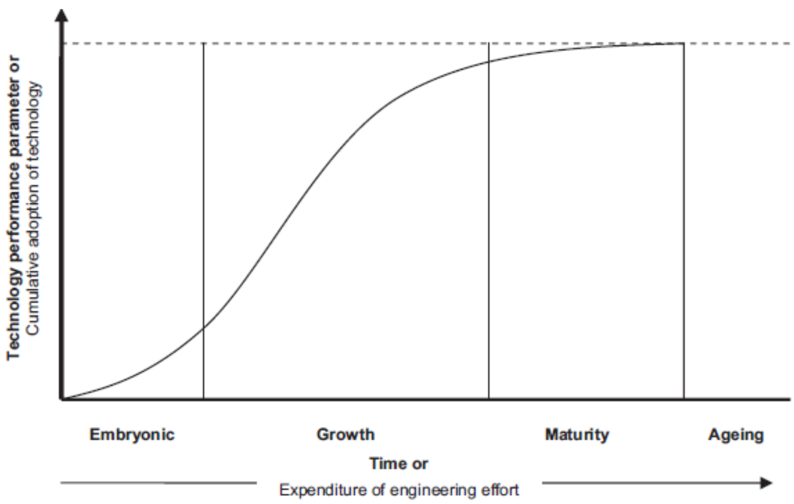


Figure 6 - Advances in a technology. Source: Cetendamar et al., 2010 *in* Taylor & Taylor, 2012

Complementary Assets

Several things determine the success of a product or technology. Efficiency is one of such things, but lack of expertise in issues such as the ability to market, regulatory knowledge, production capacity or distribution channels may hinder even the best.

History has shown the necessity of complementary assets on several occasions, being riddled with dozens of innovators that could not succeed in their ventures exactly because they lacked access to the market, production, distribution and service capability, or other skills that are crucial to being able to take to market. De Haviland's aircraft loss to Boeing, EMI's CT scanner loss to GE, R.C. Cola's Diet Coke to Coca-Cola are but a few of the examples one easily gathers.

However, even with access to these assets, some innovators have lost their battles. Although a competitive advantage, these not always suffice to create the edge that characterizes a dominant design. One such case was the already referred moment later named "The War of Currents". Although Edison was wealthier, had the system implemented in several locations, had the production capability to supply the needed products and was behind a huge propaganda machine, his claim of superiority over the AC system didn't hold, and eventually he had to concede to Tesla's.

The fact that the advances in technology may adhere to these theoretical concepts is of great significance to managers, as the strategy for entrance in a market with a specific technology and the way it is kept from spilling over to other companies' profits varies with the moment in its life-cycle.

4. Hands on a technology - how the evolution of the photovoltaic technology adheres to economic principles

Historical background

The term "Photovoltaic" stems from the conjugation of two words: Photo, Greek for "light", and voltaic, from the scientist Alessandro Volta, whose work on electricity is responsible for the understanding of reactions between different types of materials to construct a battery. As shown before, the word is particularly suited as this technology allows for the harnessing of the suns incident energy beams (photons), creating a battery from the two layers of semiconductor material.

In 1839, while experimenting with different materials, Edmond Becquerel, a French nineteen year-old experimental physicist discovered the photovoltaic effect - the direct conversion of sunlight into electricity.

In the 1860s, while conducting underwater tests using selenium, Willoughby Smith discovered that this material reacted to sunlight so as to let electricity flow. When in darkness, this material would act as an isolator. Later work by Adams and Day, led to the systematization of this knowledge, proving that no heat exchange nor moving parts were needed to convert electricity and granting a comment from Werner von Siemens (one of the founders of Siemens) as "scientifically of the most far reaching importance". If he had only known it would still be one hundred years until the trend started picking up...

Intrigued by these phenomena, several scientists began research on the properties of selenium, and in 1883 Charles Frits, an American inventor used this material to create the first solar cell. However, as the power output was very small and so many cheap alternatives (coal, gas...) existed, not many found this technology promising enough to elaborate on.

In 1905 Albert Einstein researched light properties, publishing a paper entitled "On a Heuristic Viewpoint Concerning the Production and Transformation of Light" where he theorized about the duality of particle/wave, while explaining the reason as to why the selenium cell produced electricity. Einstein further anticipated that silicon would have the same type of properties and would eventually be awarded the Nobel prize for it in 1922.

In 1931 the first module was constructed. From an array of selenium cells, Lange, a German scientist, attempted to bring the output to more considerable levels. However, not only was the output meager, but the efficiency declined rapidly when exposed to higher levels of radiation.

In 1953 Fuller and Pearson were working in the Bell Labs when by accident they discovered that two layers of silicon doped with different metals produced much higher outputs of electricity. In fact, these solar cells were deemed "high powered solar cells", although efficiency only reached as high as 6%, and saw its application restricted to satellites. The New York Times announced this discovery as "The beginning of a new era", leading to a future where all the energy needed would come from the conversion of light into electricity.

In 1955 Hoffman Electronics announced a commercial PV module with 2% efficiency and a modest 1500$/W. These values account for the dormancy of such a power source up until the first oil shock.

As a measure of interest of the consumers and technical community one may imagine an index composed of the number of times a specific subject is mentioned in published literature. As Google now offers such a tool, for the case in point, the research for published words focused on key words such as "solar energy", "photovoltaic" and PV. The graph obtained is as follows:

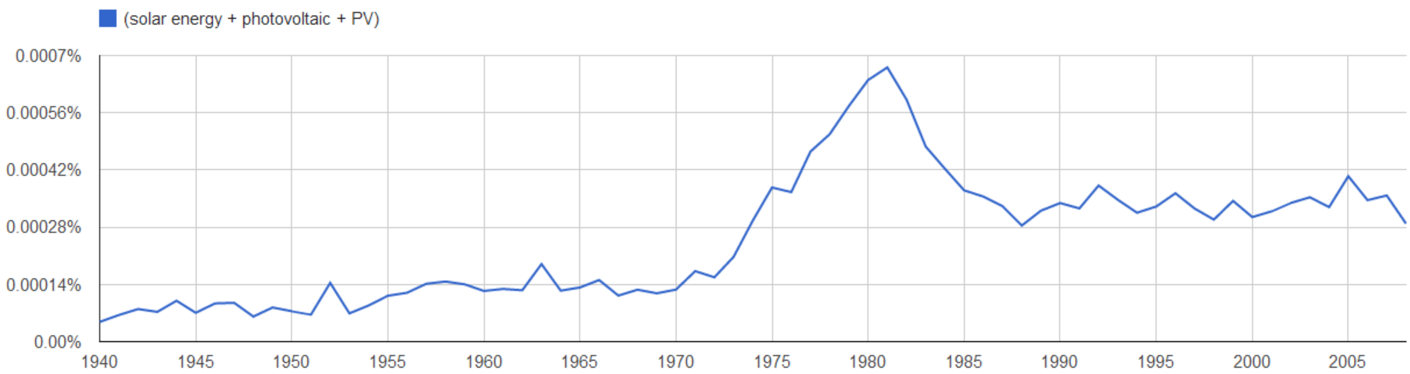


Figure 7 - Evolution of published articles on solar energy. Source: Google

It is no surprise to see the match between key dates in advances in this technology and the peaks of the graph, nor is the fact that the oil shocks in the 70s decade gave a tremendous push to the awareness that alternatives had to be sought.

In 1957 a patent was filed on behalf of AT&T, a communications company, that accounted for 8% efficiency in a single cell, and in 1958 due to Dr. Ziegler's persistency in the use of this sort of equipment instead of batteries, the first solar powered satellite was launched, having stayed active for 8 years.

In 1963 the largest PV array was installed by Sharp, totaling a whopping 242W (the equivalent to a single present day module). It was not until 1966 that the first 1kW array was put in service, this time on the Orbiting Astronomical Observatory. In 1972 over one thousand satellites were equipped with solar powered batteries, which meant that the funding for research at high level institutions was granted.

The evolution of efficiency also meant the decrease in costs, and the 70s decade saw several projects advance, such as a solar powered school in Niger, the "solarization" of the US Coast Guard's buoy system, US Southern Railway's adoption of solar powered lighting for crossroads, the use of solar powered repeaters for Australia Telecom and many other applications. This trend was significantly aided by the 70s oil shock, which saw the oil prices soar and led users to seek alternatives.

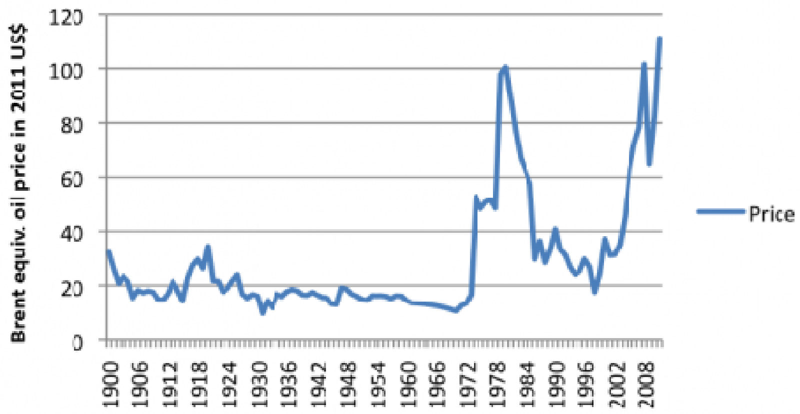


Figure 8 - Historical oil prices in 2011 dollars. Source: 2012 BP Statistical Review

The 80s decade brought about the ubiquity of solar powered gadgets, from calculators to wrist watches, the small devices ran of sufficiently low power to allow for such a solution, but the 90s was the decade of government backed tariffs that clearly offset adoption. From Germany's 100.000 solar roof's program, to Japan's 70.000, the need to provide for a greener alternative was of major importance. Another market arose with the constant downward evolution of prices and the competitiveness in the use for electrification of remote areas, as the cost for centralized production and transport of energy was not economically justifiable, but the development needs were present.

Another important aspect to the development of the technology and the creation of sustained market conditions was the leniency when it came to subsidizing the renewable alternatives. The lack of internalization of negative externalities in the use of fossil fuels allowed for it. These aspects are explained further ahead, but also justify the boom in the application of the present technology, creating demand.

As applications evolved so too evolved the need to understand the nature of the costs. The following graph shows the breakdown of the costs in a solar PV generation unit, by type:

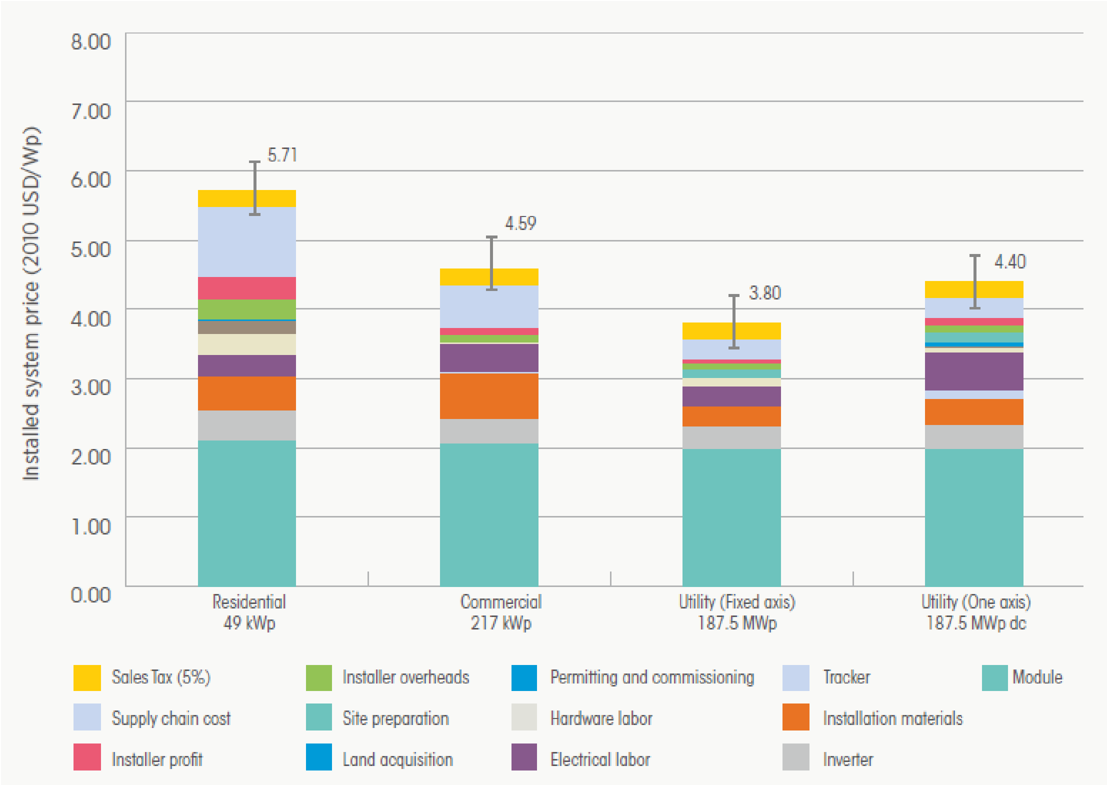


Figure 9 - Breakdown of installation cost. Source: Goodrich, 2012

As it is simple to see, although other costs are highly variable according to the type of installation, the cost of the module itself is constant.

As a major part of the overall cost is the module and this is independent from the specific policies of countries toward the technology, this work-project centers its attention on the evolution of these costs, and not on the remainder of the components in the balance of system.

The technological particularities

Having gone through the basics of the technology and considering the technology life-cycle discussed from a more theoretical point of view, it is now interesting to approach the evolution of this concrete technology.

As a sum up of investment conditions and technological breakthroughs, the following graph shows the evolution of the distinct technologies' efficiencies:

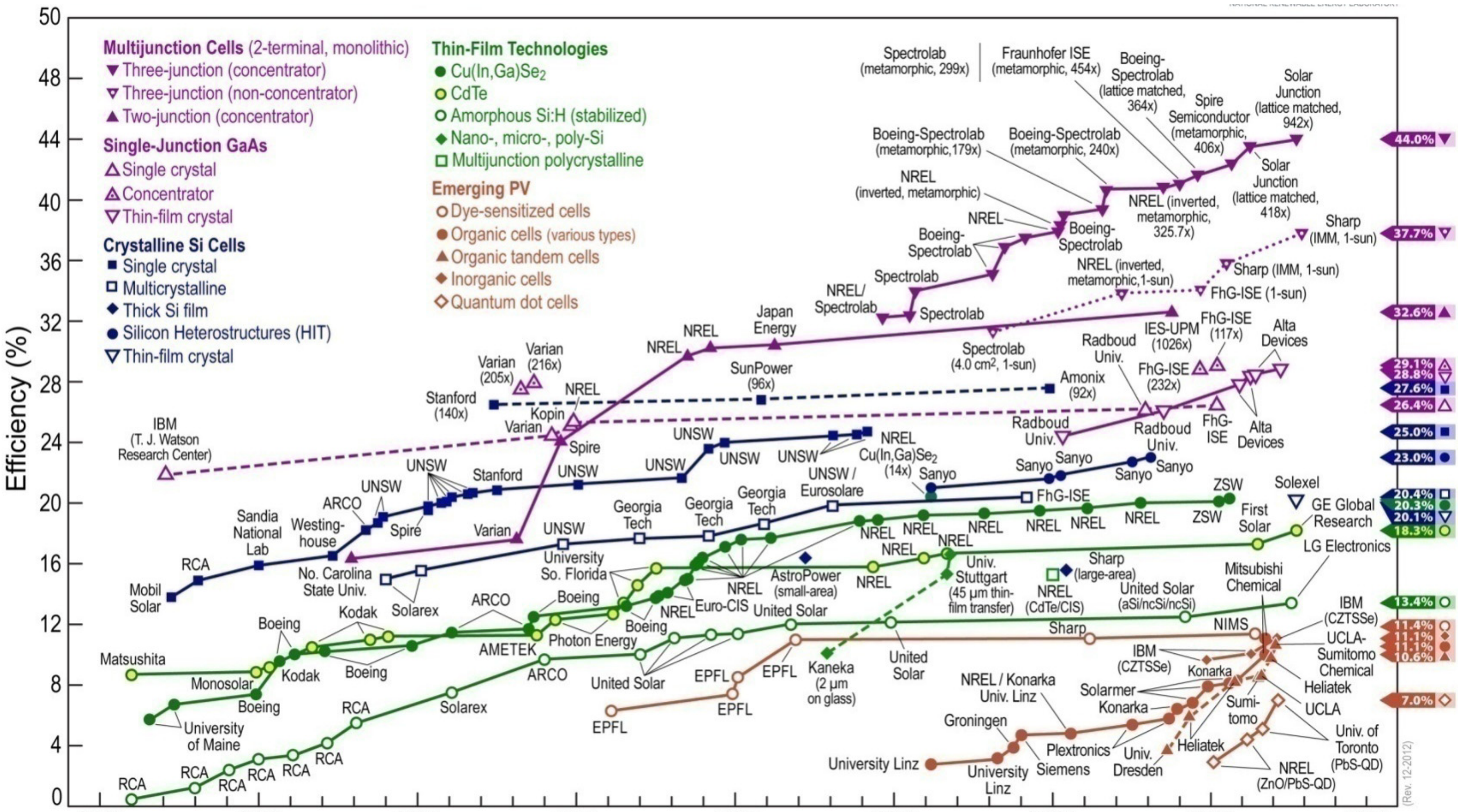


Figure 10 - Best research cell efficiencies. Source: NREL, 2013

One immediate observation is the number of coexisting sub-technologies and the fact that the effort of improvement has not yet encountered a dominant design. In fact, according to authors Heuvel & Berg (Heuvel, S., Bergh, J., 2009), maintaining several types of cell may be important to stimulate competition and progress, avoiding an early lock in. This view implies that the evolution of the different types of cell is still concurrent, and the emergence of a dominant design has not happened.

To further understand the issue, one must also account for the roles of institutions other than supplying firms in the process of the selection of the "champion cell". Indeed, the volume of market has had much to do with the evolution of the efficiency/cost indicator.

The relationship between the demand volume and the unit cost has been established to most products as an inverse one, and the PV is no exception. As may be seen in the following graph, the cost of the Wp has decreased exponentially.

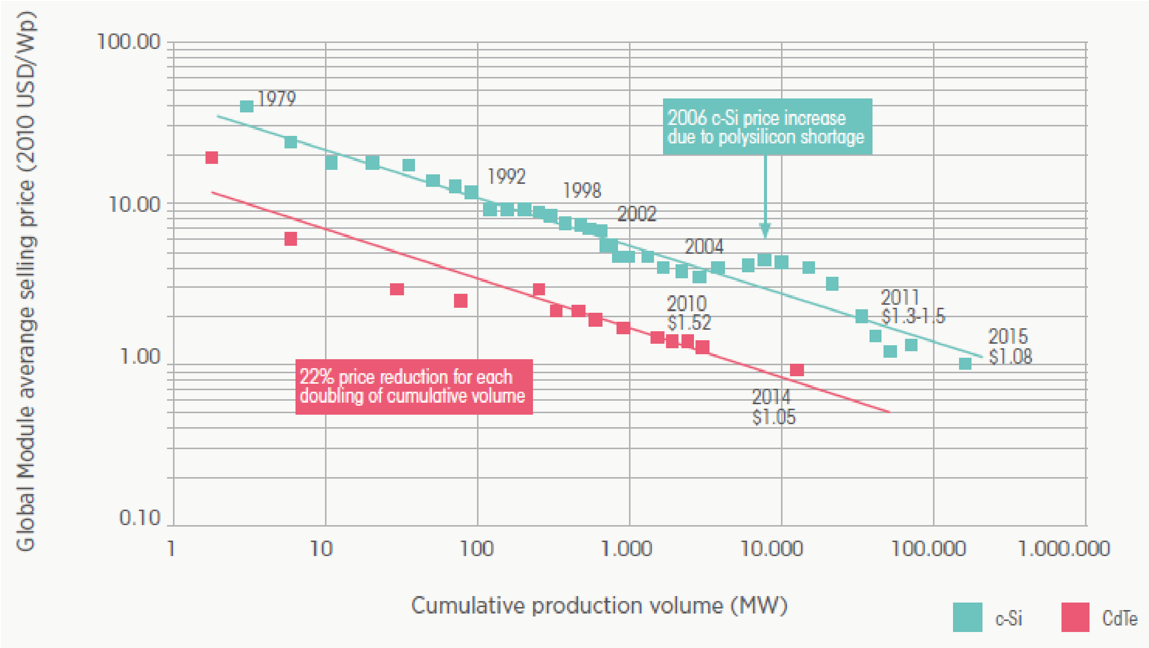


Figure 11 - Evolution of cell prices. Source: IRENA with data from EPIA

This trend allows the inference that as markets develop and the technology evolves, the penetration of this type of energy production will be exponential. However, this is not a perfect market, but a tampered one, as governments create special regulations that allow for special tariffs for PV technology.

The production of electricity from fossil sources causes pollution. Although a known fact, governments have thus far been reluctant on internalizing the negative externalities inherent to these fuels, making them more affordable than its true cost.

The search for a sustainable way of producing electricity has been a priority, but in a development phase the costs of implementation showed little market except for the electrification of distant rural areas, with difficult access to the network infrastructures. In recognizing the need for an alternative, and considering the foreseeable nature of decreasing costs with mass production that would allow for process innovations, several countries developed an array of subsidies to energy production based on renewable sources.

The two most popularized types of subsidy were the "up front payment" and the "feed in tariff". Though both types of subsidy struggle with the public opinion that the market should be left to regulate itself, the latter clearly was the one most adopted, as it allowed for the alignment of incentives of the government with those of the producer, as the gains were proportional to the amount of energy actually delivered to the system, and not just to the installed power that could lead to an early abandonment. More recently, this type of subsidy has been complemented with measures such as the "net metering" that obliges producers to consume part of the produced energy at cost, only receiving the value for the net supply of energy to the grid. The following graph systematizes the strategies for the development of renewable-based energy alternatives, considering the innovation-oriented perspective:

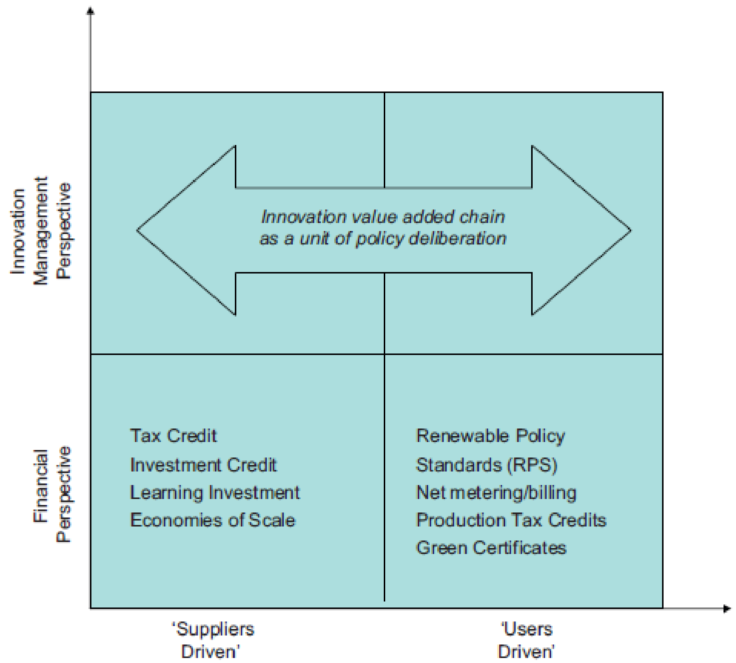
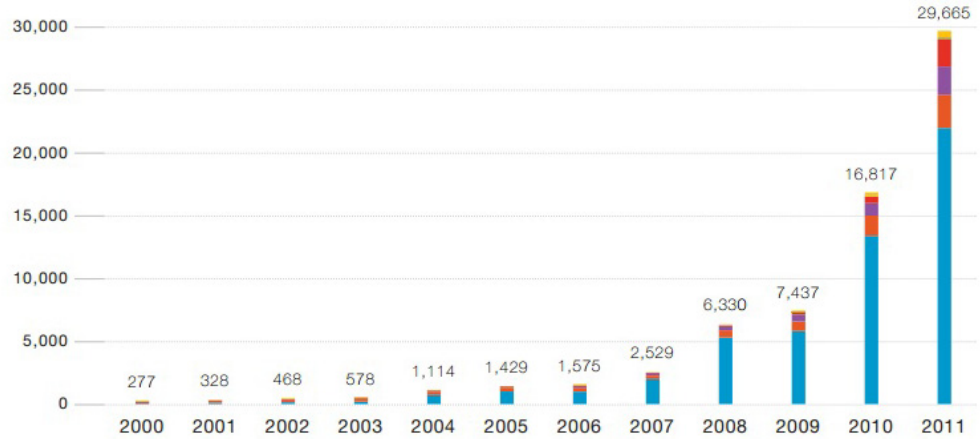


Figure 12 - Strategies for development. Source: Shum, Watanabe, 2009

The evolution of the PV market

The Market

From 2000 to 2010 the market for PV installations has increased twenty-seven fold and even in a world economic downturn as registered in 2011, the increase year-on-year was of 76%. The following graph details the evolution of the markets by geography:



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
ROW	88	56	80	77	29	10	105	42	76	80	284	508
MEA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	21	45	131
China	0	11	15	10	9	4	12	20	45	228	520	2,200
America	23	31	46	65	92	117	149	212	349	539	983	2,234
APAC	114	136	186	225	276	296	322	283	563	766	1,618	2,653
Europe	53	94	142	201	708	1,002	987	1,972	5,297	5,803	13,367	21,939
Total	**277**	**328**	**468**	**578**	**1,114**	**1,429**	**1,575**	**2,529**	**6,330**	**7,437**	**16,817**	**29,665**

Figure 13 - Evolution of global annual installations. Source: EPIA

Naturally these results cannot be dissociated from the governmental incentives mentioned above, but do show the propensity of the market to absorb the technology at its current developmental stage.

The Production

The production has seen a major shift in geography for the past few years. As the following graph shows, the initial research intensive years saw must capacity coming from Japan and Europe, but as the diffusion of the know-how took charge, the economies possible in China offset the scale and draw most of the attention.

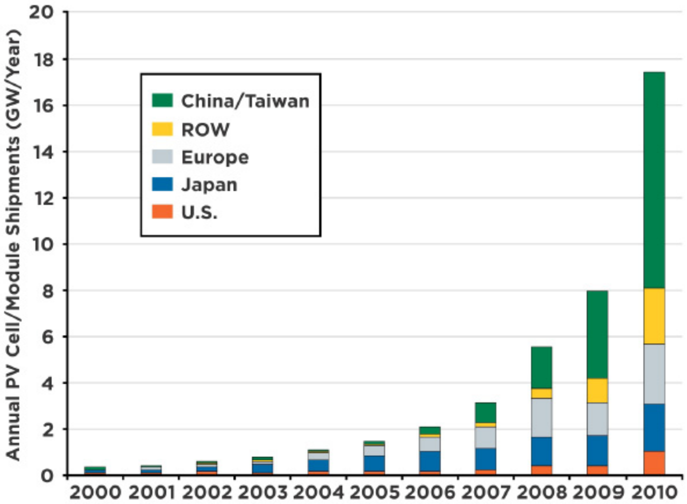


Figure 14 - Regional PV cell shipments. Source: Sunshot Vision Study, US DOE

However, even if production is mostly done in China, it is in Europe that the modules are installed.

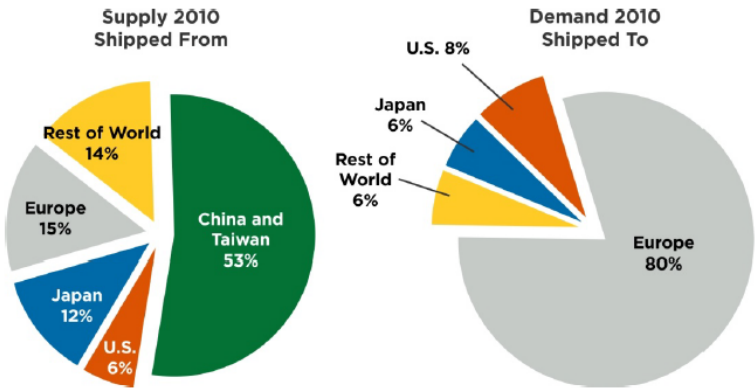


Figure 15 - Global supply and demand for PV. Source: Sunshot Vision Study, US DOE

The recent downturn in prices seem not to have been exhausted. According to a poll of experts, the future is yet bright for process improvements that will lead to a further drop in prices.

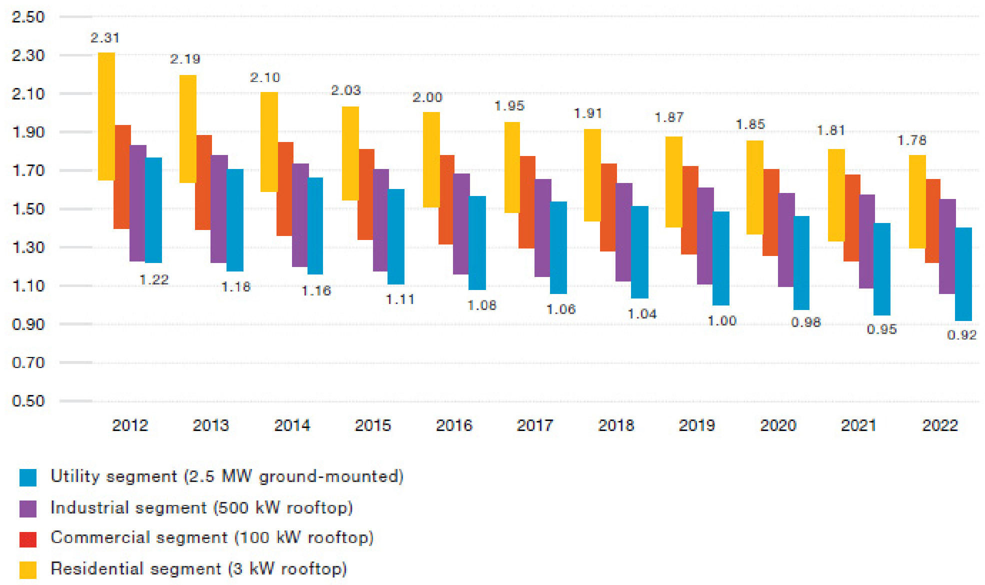


Figure 16 - Evolution of future PV prices. Source: EPIA, 2012

With the drop in price, the economic feasibility should be a game changer, allowing for grid parity - a state in which energy with renewable sources would be as expensive as the one produces with fossil fuels - and for consumers to opt without economic consequences.

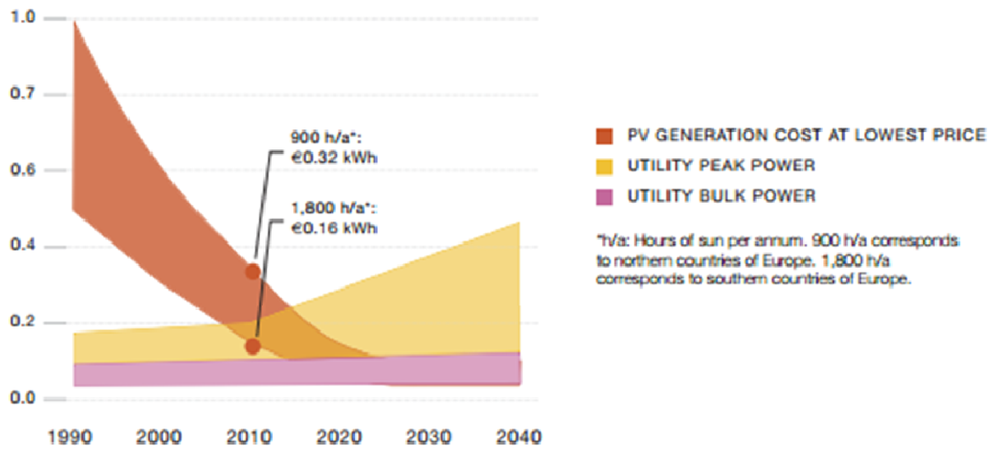


Figure 17- Cost trend and grid parity. Source: EPIA, 2011

Considering the history, developments and market of the photovoltaic technology, as well as the foresight of several experts one may now infer the moment in the life-cycle of the technology as was seen in chapter 3.

5. Conclusions

When the team of the Lisbon MBA International addressed the problem of entering the Brazilian market with the Photovoltaic technology as it would apply to micro-generation, the main concerns were how to reach the potential customers. The focus on the technology was cleared away by EDP, as the crystalline silicon based modules were chosen due to the fact that this technology had then an over 85% penetration in the world market.

However, as was seen in Chapter 3, the support for the adherence to a specific technology should stem from the future envisioned to such a technology and use all information available to determine if the moment is right for an entrance in the market. This calls for the need of an holistic approach to the product being sold. Not only is the road to market important, but the moment chosen to put the strategy in place and the bet on the technology also play an important role.

To better understand the possible solutions for EDP and the consequences of an entrance in the market with complete disregard for the moment in the technological cycle, chapter 3 synthesized the pertinent concepts and frameworks. As discussed, if the technology is still at an early development stage, it should be more interesting not to enter the market and wait for further developments.

As the world market and prospects needed to be assessed, in chapter 4 there was an effort to present the flows of equipment in the world, as well as uncover the current perspectives on what is foreseeable in the upcoming years.

With these findings and frameworks, there is now the attempt to rationalize the moment in the life-cycle of the PV technology and draw inferences on management's needed positioning when considering the entrance to a new market.

Based on available international studies, it became apparent that the market for PV is now at an exponential phase. Several elements have contributed to this, such as the Kyoto Protocol, or the recent Japanese Tsunami that led to the instability of a nuclear power plant and fear for the remaining facilities all over the world. Another key aspect relates to the decreasing trend in the manufacture costs that allow several of the greener alternatives to energy production to be accessible and business worthy. These, along with the conscience of the need for sustainable use of Earth's resources, were but a few of the reasons behind the trend for greener alternatives, and the low impact of the PV makes it a premium candidate.

However, in the same chapter, market adoption is also confronted with the fact that several designs still exist. Based on figure 10 alone one still sees the development of several parallel solutions, instead of the sole evolution of previous developments that usually characterizes the moments after the emergence of the "Dominant Design" (Chapter 3).

These two facts seem indeed concurrent, and but for the role played by elements other than efficiency, the immediate take would suggest the PV technology to be at an "era of ferment". However, as seen in chapter 3, other elements do play a decisive role.

The simple fact that the materials used in the production of the PV cells are different, and of a range of prices, alerts us not to judge the sub-technologies simply on the efficiency parameter. Indeed, as the market is diverse due to the nature of the possible applications (from orbiting satellites to applications in the Sahara desert), one may expect that one technology may be mainstream, while others occupy the niches. For comparison one need only remember that even though the CD was the format most sold, vinyl never actually exited the market.

The ability to procure silicon at low prices is one factor to be considered in how this technology became the most common one, but several other aspects need to be accounted for.

In a globalized world, with the ease of knowledge transference, not always is the life-cycle linear. As development and production are more and more specialized activities and are not made by the same entities, the massification of production is now more likely to happen before research has had time to converge into a single model. In that sense, China's production capacity has shifted many products' markets, and the PV is definitely one of them.

As seen in Chapter 4, with China's production capabilities came a substantial drop in the modules' prices, creating a generalized pull from a subsidy-distorted market. Even if the technology was not set for massive adoption, the complementary assets (Chapter 3) such as the production capability or the regulatory distortions (subsidies) pushed for the dominance of the crystalline silicon based module.

The growth of adoption, the little technological advances registered in the recent years and the shift toward process improvement documented in the several studied sources direct the pinpointing of this technology as well within the growth phase, in an "era of incremental change".

The growth moment in the life-cycle implies a standardized product, commoditized in its specifications and interface with other technologies, simplifying the introduction on a market. Additionally, the fact that EDP in not aiming to become a producer of technology but simply a marketer means that this company's power toward suppliers is increased, as a commodity may be sourced with greater ease. Further benefits to the use of a technology in the growth phase include the possibility of use of the expertise gathered from other entrants, the fact that less education of the market is needed (lower marketing costs). On the other hand, the entrance to a market with a commoditized product is a challenge. In these cases, a company's reputation is the main differentiator, not rendering the outlook for EDP in the best situation as its name is attached to the energy distributor's "curse" of being blamed for outages that are due to upstream events, such as the unavailability of power plants.

This work set out to clarify whether this was the correct moment to invest in a concrete technology, based on what could be apprehended from the technological life-cycle models, the available historic studies and forward looking analysis. The main issue was not to disprove the idea of investment in Brazil, but to give it a more formal academic context to justify the option for the silicon based technologies.

As became evident through the analysis of the market and the evolution through the commoditization of this technology, it is this author's belief that the choice in technology is a sound one, although the risk of a mature company entering a commoditized market is not one to be disregarded and may be dealt with through management options such as the spin-off and rebranding of this venture to decrease the risk.

Acronyms

EPIA - European Photovoltaic Industry Association

DOE - Department of Energy

NREL - National Renewable Energy Laboratory

IRENA - International Renewable Energy Agency

PV - Photovoltaic

Wp - Watt peak

kW - kiloWatt

kWh - kiloWatt hour

IEA - International Energy Agency

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